Unravelling the geometrical patterns and the likely physical causes of magma flow in granitic magma chambers is one of the central aspects of understanding magma chamber dynamics. In many (or most?) cases, however, direct field evidence for chamber-wide flow or convection is completely erased from the rock record. Magmatic fabrics in plutons (i.e., foliations and lineations formed during the presence of a melt; Paterson et al., 1989) commonly fail to provide unambiguous evidence for chamber-wide magma flow or convection. Instead, the preserved pluton fabrics are acquired late in magma chamber history along migrating crystallization fronts and are also easily reset by regional tectonic deformation, making inferences on large-scale convection or flow patterns difficult or rather problematic (e.g., Paterson et al., 1998).

In the present paper, we investigate an example of a post-tectonic pluton (the Říčany pluton, Bohemian Massif; figure 1) where the magmatic fabrics have not been overprinted by regional deformation and thus likely preserve a record of internal processes and magma flow. Below we present integrated structural, microstructural, and anisotropy of magnetic susceptibility (AMS) data, which revealed an unusual pattern of magmatic fabrics in the pluton. Subsequently, we discuss the significance of the observed fabrics and AMS and interpret these data to record a helical flow,
Figure 1. Simplified geological map of the Central Bohemian Plutonic Complex (b) and its position in the Bohemian Massif (a). The map is based on Czech Geological Survey 1:200 000 maps and Holub et al. (1997b). It shows the main intrusive units (or "types") with some recently published radiometric ages (Holub et al., 1997a; Janoušek and Gerdes, 2003).
Figure 2. (a) Spider plots normalized by average composition of the upper crust (Taylor and McLennan, 1995) for the three main granite varieties of the Říčany pluton, (b) spider box and percentile plots (Janoušek and Holub, 2007) showing the statistical distribution of the trace-element abundances normalized by average contents in the outer, strongly porphyritic Říčany granite, (c) chondrite normalized (Boynton, 1984) REE patterns for the three main igneous pulses within the Říčany pluton.
a rarely documented flow mechanism in granitoid plutons.

**Geological setting**

The Říčany pluton of the Central Bohemian Plutonic Complex (Bohemian Massif; figure 1) represents a post-tectonic, shallow-level intrusion emplaced into low-grade Neoproterozoic and Lower Paleozoic siliciclastic rocks in Early Carboniferous times (figure 1; 336±3.5 Ma, unpublished ⁴⁰Ar-³⁹Ar biotite data of H. Maluski, cited in Janoušek et al., 1997). In map-view, the pluton has a roughly elliptical outline (13×9 km) and is made up of three distinct granite varieties: (i) outer, strongly porphyritic, (muscovite-) biotite Říčany granite, (ii) inner, weakly porphyritic, (muscovite-) biotite Říčany granite, and (iii) a small, poorly exposed body of fine-grained, equigranular, two-mica Jevany leucogranite in the south-central part of the pluton. These granite varieties define a concentric pattern. The contact between the two porphyritic granites is gradational over several hundreds of meters; the nature of the outer contact of the Jevany leucogranite is unclear due to a poor exposure.

All varieties are fairly fractionated, peraluminous (A/CNK = 1.01-1.13), S-type granites enriched, if compared with average crustal composition (Taylor and McLennan, 1995), in Large Ion Lithophile Elements (LILE: Cs, Rb, Th, U, Sr) and depleted in some High Field Strength Elements (HFSE: Nb, Ti, HREE) (Fig. 2a). In general, the major-element compositions are comparable and do not vary greatly between the two facies of the Říčany granite.

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**Figure 3.** (a) K-feldspar phenocrysts (up to 4 cm in size) in the strongly porphyritic Říčany granite; coin for scale, (b) magmatic foliation defined by K-feldspar phenocrysts in the weakly porphyritic Říčany granite, (c) photomicrograph of a magmatic texture of strongly porphyritic muscovite-biotite Říčany granite, (d) photomicrograph of magmatic texture of weakly porphyritic muscovite-biotite Říčany granite. Crystals of main rock-forming minerals do not exhibit internal solid-state deformation. The magmatic textures are typical of all granite varieties in the Říčany pluton.
However, there are some conspicuous differences in the trace-element signatures. For instance, the central, weakly porphyritic facies shows markedly lower Rb, Sr, Ta and HREE contents at elevated Ba, U, Sr, Hf and Zr if compared with the outer, strongly porphyritic facies (Fig. 2b). All the rocks are characterized by fractionated REE patterns with a high degree of LREE/HREE enrichment. Typical is also the presence of Eu anomalies, the magnitude of which increases outwards, reaching its maximum in the strongly porphyritic Říčany granite (Fig. 2c). The degree of fractionation decreases from the pluton margin inwards, the outer, strongly porphyritic granite being more evolved than the central, weakly porphyritic granite (Janoušek et al., 1997). The position of the Jevany leucogranite is, to a large extent, independent and its genetic relationship to both the Říčany granite varieties still poorly constrained (Němec, 1978).

Magmatic fabric and anisotropy of magnetic susceptibility (AMS) of the granite

Mesoscopic foliation in the porphyritic granites is defined by a planar shape-preferred orientation of biotite and K-feldspar phenocrysts, lineation being mesoscopically indiscernible (Figs. 3a and 3b). At the micro-scale, no evidence for sub-solidus deformation was observed throughout the pluton (Figs. 3c and 3d). The foliation dips steeply (70-80°), is subparallel to the outer contact of the pluton and is thus clearly discordant with the regional host rock structures (Fig. 4).

We used the anisotropy of magnetic susceptibility (AMS) method to investigate the magnetic fabric of the Říčany pluton in order to corroborate the structural data and to quantify the fabric parameters in the pluton. 71 oriented samples were collected using a portable drill at 31 sampling sites. The AMS was measured with the KLY-4S Kappabridge apparatus...
and statistical analysis of AMS data was performed using the ANISOFT package of programs.

The AMS data are represented by the $k_m$, $P$, and $T$ parameters defined as follows $k_m = (k_1 + k_2 + k_3)/3$; $P = k_1/k_3$; $T = 2\ln(k_2/k_3)/\ln(k_1/k_3) - 1$. The $k_m$ parameter represents the mean bulk magnetic susceptibility reflecting the qualitative and quantitative contents of magnetic minerals in the rock. The $P$ parameter, called the degree of AMS, reflects the eccentricity of the AMS ellipsoid and thus indicates the intensity of the preferred orientation of the magnetic minerals in the rock. The higher the $P$ parameter, the stronger the preferred orientation. The $T$ parameter indicates the symmetry of the AMS ellipsoid. It varies from $-1$ (perfectly linear magnetic fabric) through 0 (transition between linear and planar magnetic fabric) to $+1$ (perfectly planar magnetic fabric). The orientations of the magnetic foliation poles and the magnetic lineations are presented either in a contour diagram in the geographic (in situ) coordinate system or as locality means in a map.

The mean bulk magnetic susceptibility of the analyzed samples is low, ranging from $13.13 \times 10^{-6}$ (SI) to $10.53 \times 10^{-6}$ (SI). Such a low susceptibility (in the order of $10^{-5}$) is characteristic of paramagnetic granites (Bouchez, 1997), in which the main carriers of AMS are paramagnetic minerals. The degree of AMS (represented by parameter $P$) ranges from 1.009 to 1.149 in the strongly porphyritic granite and from 1.014 to 1.363 in the weakly porphyritic granite. The $T$ parameter ranges from $-0.754$ to 0.904 in the strongly porphyritic granite and from $-0.667$ to 0.970 in the weakly porphyritic granite. No significant spatial variations in the degree of anisotropy or shape of the AMS ellipsoid were revealed in the pluton. In the Jevany leucogranite, the $P$ parameter ranges from 1.07 to 1.27 and the $T$ parameter ranges from 0.1 to 0.9.

The magnetic fabric pattern (AMS) of the Říčany pluton is characterized by margin-parallel, moderately to steeply dipping magnetic foliation (Fig. 5); its geometry is consistent with the orientation of mesoscopic magmatic foliation. Foliation poles tend to concentrate along the periphery of the stereonet (Fig. 5). Magnetic lineation steepens significantly as a function of distance from the pluton margin. In the outer part of the pluton, the lineation plunges shallowly (0-20°) and is subparallel to the contact whereas in the center lineation dips steeply (60-70°) with variable trends (Fig. 5).

**Discussion and conclusions**

Our structural and AMS data do not comply with existing models proposed for the emplacement of elliptical, onion-skin plutons (e.g. single-blob or nested diapirism, ballooning, laccolith-like emplacement). We interpret the mesoscopic and magnetic fabrics in the Říčany granite as a result of helical flow (as defined by Fowler, 1996). In our model, we consider the strongly and weakly porphyritic granites as two nested magma batches having different viscosities during emplacement. We envisage that the difference in K-feldspar phenocryst content in the two granites caused significant difference in their viscosities: the
outer, strongly porphyritic granite presumably had viscosity of a higher order of magnitude than the central, weakly porphyritic granite. This assumption is in agreement with an exponential increase in viscosity with crystal content as predicted by the Einstein-Roscoe equation for solid-liquid mixtures. Considering the Říčany pluton as a steep-sided cylindrical body, we can apply the Hagen-Poiseuille equation for fluid flow through a pipe to infer the flow mechanism within the pluton. Contrasting viscosities of the two magmas then would cause their different velocities during ascent. Consequently, faster subvertical flow of low-viscosity (phenocryst-poor) magma in the pluton center may have generated helical (subhorizontal) flow in the outer, high-viscosity and phenocryst-rich layer. This two-layer model explains well the finite fabric pattern, with concentric, steep foliations and magnetic lineation being subhorizontal along the pluton margin and subvertical in the center. Taking into account the shallow emplacement level of the Říčany pluton, the pluton may be viewed as a conduit linking a deeper magma chamber with a volcanic system at the surface.

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